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Method for determining frequency sub-band division in modems based on multicarrier ~~modulation technique and~~ system utilizing the method

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The invention relates to a method according to the preamble of claim 1 for dividing the transmission bandwidth into data-transferring subchannels of desired bandwidths and carrier locations in modems based on multicarrier modulation technique.

The invention also relates to a system for optimizing subchannel allocation in modems based on multicarrier modulation.

Accordingly, the invention concerns a method capable of offering modem connections protection against radio-frequency interference occurring at frequencies not known *a priori*. The invention further concerns an apparatus giving protection against such radio-frequency interference on a modem connection. The method can be used in modems based on conventional linear modulation methods: QAM (Quadrature Amplitude Modulation) and CAP (Carrierless Amplitude/Phase Modulation).

Copper lines are finding use for transferring data at increasingly faster rates. A task force of the ETSI (European Telecommunication Standards Institute) is currently working on standard specifications of the VDSL (Very High Speed Digital Subscriber Line) modem. The maximum data rates will reach tens of megabits per second and the frequency band used for data transfer will extend from 300 kHz to 30 MHz.

Operation at this frequency range over subchannels having a bandwidth of several megahertz will make the system subject to interference from different kinds of radio-frequency emissions particularly in countries using overhead wireline cables for subscriber connections (as is the case in rural Finland, for example). The frequency range is also allocated for use by a plurality of AM radio stations and even radio amateur activities. Such radio emissions can cause disturbance in the modem

receiver by way of being coupled onto the overhead wireline cable, whereby a portion of the captured energy is converted into a so-called transverse interference signal that may be transmitted over the cable up to the modem receiver. On the other hand, the modem connection itself can cause interference at radio frequencies inasmuch the modulated signal transferred over the cable involves power transmission at radio frequencies, whereby a portion of the modem transmitter output power may be emitted to the environment.

As to the design of a modem, radio-frequency interference can be divided into two categories: interference at *a priori* known frequencies and interference at random frequencies that cannot be known *a priori*. One kind of *a priori* known interference is related to that caused by radio amateur transmissions owing to the fact that radio amateur activities are concentrated on certain frequency bands allocated by international standardization bodies. In contrast, emissions of the multitude of AM stations must be included in the group of random interference whose frequencies cannot be considered known *a priori* during the design process of a modem, since the transmission frequencies of the stations may vary widely from country to country.

The connection in a given direction (that is, from the subscriber to the switching center in the US (upstream) direction) or from the switching center to the subscriber in the DS (downstream) direction can be implemented using a single channel (1) or a plurality of subchannels (2) as illustrated in Fig. 1. When a multicarrier system is adopted, the subchannels may be separated by a frequency band (3) (conventionally known as a guard band) over which practically no power is transmitted or, alternatively, the subchannels may overlap to a certain extent as shown in Fig. 2. While the overlapping subchannels appear to form a continuous frequency band, the modulation technique used herein is easier to understand on the basis of multiple subchannels.

A schematic illustration of a system using more than one channel per data transfer

direction is shown in Fig. 3 for one direction. The information carried by the data (D) to be transferred is distributed between parallel branches (D1...Dn) that are upmodulated (m1...mn) each into its own subchannel across the bandwidth. In this manner, the data stream is multiplexed into subchannel signals S1...Sn, which together form the combination signal (S) to be transferred over the transmission channel. In reception, certain functions (h) (such as a portion of signal filtering) are imposed on the incoming signal (S). Next, the subchannel signals (s1...sn) corresponding to each subchannel are separated and downmodulated (m1...mn) from the incoming signal, after which the subchannel signals are subjected to other operations required at receive end, such as channel equalization, detection, clock recovery and necessary filtrations (k). Combination of the parallel data substreams d1...dn yields the received data stream (d). Thus, the received data stream (d) is identical to the incoming data stream (D) of the transmit end provided that no transmission path errors have occurred. In this text, the frequency bands corresponding to each data substream are called subchannels. However, the subchannels used for data transfer in a given direction (US or DS) need not necessarily be placed orderedly adjacent to each other in the frequency spectrum, but also other kinds of allocation schemes may be used for arranging the subchannels of opposite data transfer directions in an interlaced manner. For the context of the following discussion, the data transfer direction assigned to a certain individual subchannel is an irrelevant issue. The center frequencies of the subchannels are called carriers, whereby a system using only one channel per a data transfer direction is known as a single-carrier system and, respectively, a system using multiple subchannels per a data transfer direction is called a multicarrier system.

In a single-carrier communication system, the bandwidth of the data transfer channel at the bit rates used on VDSL connections is in the order of several megahertz, typically from 1 to 12 MHz. The amplitude and phase distortion of the channel must be corrected by adaptive equalizers of the receiver. The magnitude of amplitude and phase distortion is proportional to the channel bandwidth and, thus, to the data transfer rate (symbol rate). Resultingly, a higher data transfer rate also requires a longer

time period to be processed in the equalizers of the receiver. Such an increase in the temporal capacity of the equalizer also requires a larger number of tap coefficients. The larger number of tap coefficients in turn increases the quantity of computational steps and thus the power consumption of microcircuits, which is a critical factor in the reliability of electronic equipment. However, the single-carrier communication system has the simplicity benefit of fixed structure in the transmitter and receiver filters as compared with those of multicarrier communication systems.

The subchannels of a multicarrier system may be allocated equal or unequal bandwidths in the frequency spectrum, and they can be spaced at equal or unequal distances from each other over the frequency spectrum. In a conventional DMT (discrete multitone) modulation scheme, all the subchannels have an equal bandwidth and they are equispaced. The DMT modulation is implemented with the help of a filter bank that at the transmit end performs an inverse discrete Fourier transform (IDFT) and at the receive end a corresponding discrete Fourier transform (DTF) [Lee & Messerschmitt]. Such a filter bank that forms subchannels of equal bandwidth and equal spacing is called a uniform filter bank. Respectively, a filter bank not fulfilling the condition of equal bandwidth and/or equal spacing is called a nonuniform filter bank. The realization of both uniform and nonuniform filter banks is described, e.g. in a paper [Cox]. With the help of such filter banks, it is possible to implement both uniform and nonuniform multicarrier communication systems. A multicarrier system may also be contemplated to be comprised of a plurality of logically, but not necessarily implementation-wise, parallel-operating single-carrier systems. In Fig. 3, for example, each branch (e.g., signal chain: m1-channel-h-m1-k) can be formed by a conventional communication system based on the QAM technique. A description of the QAM basics can be found, e.g., in cited publication [Lee & Messerschmitt].

Multicarrier communication systems have an advantage over a single-carrier system in that multicarrier systems allow data streams to be transmitted over frequency bands exhibiting the best signal-to-noise ratio and, on the other hand, to avoid such

frequency bands on which interference emission from the modem operation is unallowable. A disadvantage of multicarrier systems is the complexity of their transmit and receive filter structures (filter bank) and the high ratio of peak-to-RMS signal power as compared with a single-carrier system. While the degree of system complexity increases with the number of subchannels, a great number of subchannels is advantageous in terms of the overall data transfer capacity because it offers the possibility of maximally utilizing the frequency ranges of highest signal-to-noise ratio. Given a constant data transfer capacity, the division of the channel into a greater number of subchannels requires that either all or at least a portion of the subchannels must be operated at a reduced bandwidth. A narrow subchannel bandwidth improves the system tolerance to impulse noise, since the symbol period is simultaneously extended.

Furthermore, a narrower bandwidth of the subchannel allows the use of equalizers designed for a shorter temporal length, because the narrower bandwidth reduces the transmission channel distortion. This benefit also reduces the overall number of computational operations per time unit required in the equalizers of all the subchannels. The increase in the number of subchannels is compensated for by the symbol rate reduction in all or some subchannels, which also reduces the rate of computations in the equalizers.

The following discussion is directed to elucidate the conventional techniques utilized to reduce the radio-frequency interference problem at the receive end.

In a VDSL single-carrier communication system, the bandwidth of a singular RF interference emission is typically essentially narrower than the data signal transmission bandwidth. Hence, a singular source of RF interference can be treated as a narrowband emitter in the frequency spectrum. On the other hand, the signal transmission bandwidth in the VDSL single-carrier system is so broad that the incidence of RF emissions on the transmission channel bandwidth is usually impossible to avoid. Such spot-frequency interference can be eliminated by bandstop filters. If the

frequencies of the interference emitters are known *a priori*, the problem can be overcome using bandstop filters tuned to given frequency bands and implemented using analog, digital or mixed techniques. In the case that the RF interference emitter frequencies are not known *a priori*, an adaptive filter must be used with a design capable of tuning the bandstop filter frequencies case-by-case so that they are centered at the frequencies emitted by the RF interference source.

Such fixed bandstop filters cause additional distortion which must be compensated for by increasing the temporal length of the receiver equalizers and, by the same token, the number of tap coefficients. This in turn increases the task of required computation. Moreover, stop bands falling over the data signal transmission spectrum deteriorate the signal-to-noise ratio, sometimes even drastically [Salz]. In practice, the use of an adaptive filter means that the temporal length of the linear equalizer (FFE) in the receiver must be increased substantially in order to provide the equalizer with a sufficient capacity for both handling its portion of channel distortion equalization and additionally forming the required stop bands. Also the temporal length of a feedback equalizer (DFE) must be increased to make it capable of handling its respective portion of channel distortion equalization and, additionally, of compensating for the distortion imposed on the composition signal by the stop bands formed in the linear equalizer block. Also herein, the signal-to-noise ratio degradation is subject to the same factors as those affecting the use of fixed-frequency bandstop filters.

In multicarrier communication systems, two conventional methods of entirely different nature may be used for protection against RF interference: 1) the frequency range affected by the RF interference may be excluded from the data signal transmission spectrum, or 2) said affected frequency range is filtered in the same fashion as in a single-carrier communication system.

In the case of RF interference occurring at frequencies known *a priori*, a practicable application of the former method requires that the subchannels used for data transfer

are placed on frequency bands free from said RF interference.

In a system suffering from RF interference at frequencies not known before, the former method is applicable to multicarrier systems of a great number of carriers up to tens or hundreds. The principle of this approach is illustrated in Fig. 4. Herein, a suitable error criterion is used for decision-making on a given subchannel (2) affected by an RF interference emission (4) and, when the level of interference is high enough to prevent said subchannel from transmission of the composition signal with a sufficiently good quality, transmission over the affected subchannel is stopped. The exclusion of a few (1 to 10) subchannels does not reduce the data transmission capacity (in bits/s) noticeably, because the contribution of any individual subchannel in the overall data transfer capacity of the system is very small. Resultingly, data transmission is arranged to take place on frequency bands not affected by RF interference. A drawback of systems operating with tens or hundreds of carriers is the complicated implementation of transmitter and receiver structures and a high peak-to-RMS signal power ratio.

In a multicarrier communication system operating with so few subchannels that barring data transmission even on one of them would degrade the data transfer capacity in a drastic manner, RF interference occurring at random frequencies must be attenuated using adaptive filters principally in the same fashion as in a single-carrier system. To encounter this demand, the number of computations required per time unit must be increased, which causes higher power consumption in the microcircuits. Later in the text, the peak value of computations per time unit will be called the computing capacity.

If the interference occurs at a sufficiently low power level, the situation can be handled by reducing the bit rate of the affected subchannel, whereby the interference tolerance increases with the reduction of detected signal levels. Also this technique is more suitable for use in a system having a high number of subchannels (from tens to hundreds), because the exclusion of a few subchannels does not reduce the overall

data transmission capacity noticeably.

It is an object of the present invention to overcome the drawbacks of the above-described techniques and to provide an entirely novel type of method for allocating the subchannels used by modems in a multicarrier communication system and for optimally allocating the available computing capacity of signal-processing facilities between said subchannels.

The subchannel allocation according to the invention is implemented by dividing the available signal transmission bandwidth at frequencies having statistically most interference frequencies not known *a priori* into subchannels having a bandwidth narrower than that of the other subchannels.

More specifically, the method according to the invention is characterized by what is stated in the characterizing part of claim 1.

Furthermore, the system according to the invention is characterized in that the narrowest subchannels are placed on the frequency spectrum bands that are affected by the statistically largest portion of interference emissions at frequencies not known *a priori.*

Allocation of computing capacity according to the invention between the individual subchannels is implemented so that a portion larger than that of conventional allocation schemes is reserved from the available computing capacity for subchannels placed on frequency spectrum bands that are affected by the statistically largest portion of interference emissions at frequencies not known *a priori*.

In a preferred embodiment of the invention, the system is provided with a facility of case-by-case allocation of computing capacity between the subchannels either automatically or under manual control.

The system according to the invention is characterized in that allocation of comput-

ing capacity between the individual subchannels is implemented by reserving a portion larger than that of conventional allocation schemes from the available computing capacity for subchannels placed on frequency spectrum bands statistically most affected by interference emissions at frequencies not known *a priori*.

More specifically, the system according to the invention is characterized by what is stated in the characterizing part of claim 8.

The invention offers significant benefits.

The subchannel allocation scheme according to the invention provides the following advantages:

The level of interference caused by RF emissions affecting a given subchannel can be reduced, because the present approach lowers the number of interference emissions incident on a given subchannel (herein it is fully appropriate to treat the interference by the number of emissions because a single source of interference can be assumed to occur at a singular point of the frequency spectrum).

The system complexity will not be increased in an unnecessary manner, since the subchannels are narrowed only at frequencies giving the maximum benefit, where the number of extra subchannels required remains insignificant.

The allocation scheme of computing capacity between the subchannels gives the following benefits:

In the system design phase, the available computing capacity can be allocated to subchannels on which its use is maximized on a statistical basis.

The available computing capacity can be allocated during the use and/or operation of the system manually or automatically on a case-by-case basis so as to achieve

maximum efficiency.

In the following, the invention is described in more detail with reference to exemplifying embodiments elucidated in the appended drawings in which

Fig. 1 is a graph illustrating signal transmission by prior-art techniques on a single, continuous frequency band;

Fig. 2 is a graph illustrating signal transmission by prior-art techniques on a plurality of nonoverlapping subchannels;

Fig. 3 is a graph illustrating signal transmission by prior-art techniques on a plurality of partially overlapping subchannels;

Fig. 4 is a block diagram illustrating a one signal transmission direction (US or DS) of a prior-art multicarrier communication system; and

Fig. 5 is a graph illustrating an allocation scheme according to the invention of the full signal transmission bandwidth into a plurality of subchannels in the modem equipment.

The abbreviations used in the text of this publication are:

AM	Amplitude modulation
CAP	Carrierless Amplitude/Phase modulation
DFE	Decision-feedback equalizer
DFT	Discrete Fourier Transform
DMT	Discrete multitone
DS	Downstream (data transfer from switching center toward subscriber)
ETSI	European Telecommunication Standards Institute
FFE	Feed-forward equalizer
IDFT	Inverse Discrete Fourier Transform

QAM Quadrature Amplitude Modulation

US Upstream (data transfer from subscriber toward switching center)

Tap coefficient Coefficient of the digital filter tap used for multiplying the sampled value of the signal to be processed.

Accordingly, the invention concerns a method and apparatus for protecting against RF interference occurring at frequencies not known *a priori* in a multicarrier system operating with 2 to 5 subchannels per direction of signal transmission. In this type of a system, the exclusion of a subchannel or reduction of its bit rate will affect the overall data transmission capacity of the system in a detrimental manner up to several tens of percent. In a VDSL application, the subchannel bandwidth in such a multicarrier system is in the order of 0.3 - 4 MHz, whereby RF interference can be treated as a discrete emission in the frequency spectrum in the same manner as the interference is handled in a single-carrier system.

Conventionally, the subchannels of multicarrier communication systems have been placed on frequency bands of the highest signal-to-noise ratio and, respectively, frequencies involving prohibitions of RF interference emissions are not used. To those versed in the art, proper allocation of subchannels so as to avoid RF interference at frequencies known *a priori* is obvious. In contrast, other kinds of RF interference cannot be circumvented in the system design phase by proper allocation of subchannels, because the emission frequencies of these RF interference sources may vary widely from country to country and even from site to site. In the following discussion, the term RF interference is used solely when reference is made to RF interference occurring at frequencies not known *a priori* to the modem designer.

The present invention comprises three parts of which the first one is a novel method of determining the allocation of subchannels and apparatus suited for implementing the method.

The first part of the invention is based on the fact that the disturbing effect of RF

interference is proportional to the number of RF interference sources falling on the bandwidth of subchannel. This number is a computable quantity, because this kind of interference can be treated as a point source in the frequency spectrum.

The novel concept of multicarrier system according to the invention is based on anticipating RF interference occurring at random frequencies by placing the subchannels of narrower bandwidths on frequency bands, where radio broadcast activity is highest and the frequency spectrum is most densely populated by the spot frequencies of radio stations, such a frequency range typically spanning 90 kHz – 3.6 MHz. In the implementation of the invention, the transmission direction (whether US or DS) of each subchannel is irrelevant.

The principle of subchannel allocation is shown in Fig. 5. The narrowest subchannels (2) are placed over the frequency range (5) that is statistically most affected by interference at frequencies not known *a priori*. The subchannels may be overlapping or separated from each other by a guard band. Also here, the transmission direction (US or DS) of each subchannel is irrelevant.

Obviously, the system design may be started from a single-carrier communication system whose entire transmission bandwidth is divided into subchannels that are implemented by the same design techniques as those of the original single-carrier system. The allocation of subchannels is arranged so that the narrowest subchannels are placed on the frequency ranges of the highest radio broadcast activity and the highest density of radio stations along the frequency axis. After the allocation of the subchannels, the transmission direction of each subchannel may be selected freely as noted above.

The second part of the invention is based on the following facts well known in the art:

Firstly, the number of computation operations per time unit required in an implementation of the system hardware is subject to constraints in microcircuit power con-

sumption and heat dissipation, size and cost. Later in the text, this constraint is referred to as the computing capacity.

The temporal lengths of the equalizers and/or the adaptive filters required in the different subchannels for attenuating RF interference increase with the increase of the RF interference level affecting a given subchannel.

Such an increase of the temporal length of equalizers and/or other adaptive filters necessitates use of a larger number of tap coefficients in equalizers and/or similar adaptive filters, thus involving a respectively higher number of computation steps per time unit.

The novel approach to a multicarrier system according to the invention is to anticipate the RF interference occurring at frequencies not known *a priori* by assigning the equalizers having the longest temporal length by the number of their tap coefficients or, respectively, the adaptive filters designed only for attenuating RF interference, to serve those subchannels that are placed on the frequency bands where radio broadcast activity is highest and the frequency spectrum is most densely populated by the spot frequencies of radio stations, such a frequency range typically spanning 90 kHz – 3.6 MHz.

As is evident from the examination of the situation illustrated in Fig. 5, an approach based merely on the conventional design of channel distortion equalizers does not provide the same result as that described above. Dimensioning rules based on equalization of channel distortion actually advice to reduce the number of tap coefficients, even the more the narrower the bandwidth of a given subchannel. Design rules based on the present invention teach to take the opposite approach. Accordingly, the greatest number of tap coefficient shall be allocated particularly to the narrowest subchannels. This design rule for the number of tap coefficients in practice means that the available computing capacity must be divided between the different subchannels.

The third part of the invention relates to a novel method in modem use for selecting the temporal length of equalizers and/or separate adaptive filters of RF interference, which are assigned to different subchannels, and an apparatus utilizing the same.

Parts 1 and 2 of the invention are based on *a priori* knowledge about frequency ranges affected at the highest probability by RF interference. The method used in part 2 of the invention allows the available computing capacity to be divided on the basis of statistical knowledge in an optimal manner between the different subchannels. In some individual cases it is possible that the allocation of available computing capacity based on the above-described statistical knowledge approach is not the optimal solution.

A novel concept herein is that the multicarrier communication system according to the invention anticipates RF interference occurring at random frequencies not known *a priori* by virtue of arranging the numbers of the tap coefficients of equalizers and/or separate adaptive filters of RF interference, which are assigned to different subchannels, to be so parametrized that the allocation of computing capacity between the different subchannels can be altered case by case.

It is a further novel concept that the system is provided with a mechanism capable of changing during the operation of the modem the allocation of the available computing capacity between the different subchannels by modifying the above-mentioned number of tap coefficients in order to optimize the quality and/or speed of data transmission. The criterion for optimization can be selected to be, e.g., the ratio of detection error rate to the distance between adjacent detection levels.

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